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THE O.N.E.R.A. TESTING METHODS AND THEIR RECENT PROGRESS

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ABSTRACT. Some O.N.E.R.A. hypersonic testing facilities, and conventional long run duration facilities for $2 < M < 10$ with emphasis on the R3 wind tunnel ($8 < M < 10$) useful for heating research (i.e. rocket stage separation, hypersonic air intakes, etc.) are described. The slow compression R4 wind tunnel for $M = 14$ and the hot shot wind tunnel for ($15 < M < 20$) are also described. Frozen flow phenomena at the nozzle throat and their effects are also given.

Resumé

Among the test facilities available to the ONERA* for hypersonic research, some are of a now classical type (long-run duration wind tunnels) and others of a more recent design (hot-shot slow compression wind tunnel). We will describe recent progress in readying the tunnels and will give a few typical examples of research actually in progress.

1. Long-run duration wind tunnels (~ 10 sec). After a brief discussion of the organization and the general performance of the group of blowdown wind tunnels ($2 < M < 10$), the R3 wind tunnel ($M = 8 - 10$) will be described in more detail, whose design is especially suitable for research on kinetic heating.

Other examples given include: separation of rocket stages; hypersonic air intakes; study of effect of atmospheric gusts on a projectile; magnetic model suspension in the tunnel.

2. Slow-compression wind tunnel (R4, Mach 14). This wind tunnel, whose reheater is designed as a piston which, in a long tube, gradually compresses the mass of air to be reheated, is characterized by a highly clean flow ($M = 14$) and by the relatively long runtime of the blowdown (100 - 200 msec). These properties have made this tunnel a highly useful facility for basic research.

3. Hot-shot wind tunnels (Mach 15 - 20). Some original aspects of the /2
hot shots of the ONERA (ARC 1 and ARC 2) are outlined: method of direct power supply from the EDF national grid system; runtime of blows (100 msec); recent improvements in the arc chamber permitting quasi-constant pressure and satisfactory homogeneity of flow.

Suitable mechanical devices permit a variation in angle of attack by 15° or

* National Aerospace Research and Development Administration (France).

** Numbers in the margin indicate pagination in the foreign text.

a rotation through 180° of the model about its axis, in the useful section of the gust.

Some recent examples of results with these two wind tunnels are given.

In addition, the phenomena of frozen flow at the nozzle throat and their effect on the flow parameters are described.

Introduction

/3

Until 1956, French research in the high-speed area had been limited to the supersonic range. The C4 wind tunnel of Vernon, placed in service in 1951, was the most powerful test facility available at that time. There is no need to review here the characteristics of that tunnel ($M \leq 4.4$, $p_1 \leq 10$ atm, test section 40×40 cm^2, power 14,000 kw), since many of the members in the audience have contributed to its initial study and its practical development. It is my agreeable duty to emphasize that this wind tunnel, so far as I know, is the first tangible example of an important piece of work led to completion by a team of French and German engineers and technicians, working in close cooperation under a common management.

Starting in 1957, our research became increasingly concerned with the hypersonic range; at that time, I was entrusted with the task to create, at the ONERA, the necessary experimental research facilities. Due to the excellent relations existing between our two establishments, it was agreed that the ONERA would first direct its efforts toward wind tunnels of relatively long runtimes (100 msec and more) whereas the LRSL specialized in technology of shock tubes and ballistic capabilities in view of its long experience with short-time testing.

This was the program followed for gradually readying the ONERA wind tunnels shown schematically in Fig.1.

Some of these wind tunnels (R1 and R2) are of such a conventional design as to require no further discussion. A detailed description is given elsewhere (Ref.1).

Here, we will discuss the more original and recent installations including the R3 Ch, R4 Ch, ARC 1 and 2 tunnels, followed by a summary description of the type of research done in these tunnels at present.

1. Wind Tunnel R3 Ch ($M = 10$); Fig.2

This blowdown tunnel has a maximum runtime of 10 sec (limited by the capacity of the vacuum tank). The initial pressure may reach 170 atm and the generating temperature should be at least 1100°K so as to prevent any liquefaction phenomena about the model at $M = 10$.

The solution adopted for the reheater is quite ingenious: It consists in circulating compressed air in the parallel Inconel tube clusters, through which a direct current of 4 k-amp at 500 v is fed in series. Each conductor cluster, in turn, is enclosed in a steel tube which remains almost cold during the entire run and is exposed to the operating pressure (170 atm). Thus, the conductor tubes, operating close to their fusion point, need to resist only very low charge losses between the upstream and downstream ends of the system.

During adjustment to the thermal regime preceding the run itself, the air is discharged to the atmosphere through a dual-effect high-speed valve. As soon as the desired starting temperature and pressure are obtained, the valve reverses within less than 1/100 sec and triggers the nozzle: The flow thus reaches its stationary regime within a few milliseconds. /4

At the end of the blow, the inverse process is initiated, which avoids the inconvenience of a protracted de-energizing of the model and cools the heat exchanger before complete arrest of the flow.

This particular wind tunnel is equipped with M = 8 - 9 and 10 nozzles, with only the upstream portion being interchangeable and the downstream end being fixed. Each upstream section is calculated by the method of characteristics, used for inversed flow starting from the desired Mach number which is assumed as being obtained at the exit. This solution is highly economical and practical for varying the Mach number. In addition, it furnishes highly uniform Mach number distributions in the test section.

In this wind tunnel, aside from six-component measurements performed at 20° automatic variations in angle of attack during the entire run, mainly kinetic heating tests are performed (Fig.3). Because of the instantaneous start-up of the flow, the thin-walled (1 - 2 mm) thermocouples will directly indicate the flux by their initial inclination; no correction is necessary here since the measurement is made within 1/10 sec before large temperature gradients have had a chance to become established in the wall.

Another interesting technique (Fig.4) has recently been developed, which uses insulating models made of "Silastene" coated with a thermosensitive paint (thermocolor) (Ref.2).

A comparison of the time of spin of the model with a standard sphere permits approximate quantitative conclusions; however, the main interest of the method lies in the possibility of detecting, within a single blow, any specific heating zones (flow separation, transitions, vortices, shock waves) as well as the general structure of the wall flow.

Investigations during separation of missile stages, interactions between external flow and exhaust jet of the ignited rocket stage are relatively easy, using either compressed air jets simulating the exhaust jet of the rocket, or a powder microrocket. Figure 5 shows the extensive flow separation produced around the model during a premature firing as well as the existence of a critical distance beyond which all interaction ceases. The thrust of the aft portion of the front stage (Fig.6) permits evaluating the risks encountered in such phenomena, under the effect of lateral forces that they might generate. These risks are quite real; it actually happened during the abort of the first Antarès rocket fired by the ONERA in 1958 that this phenomenon was discovered in the wind tunnel and that subsequently this particular testing technique was developed to ensure success of later launchings.

The rapid establishment of flow in the R3 wind tunnel recently permitted checking on the possibility of starting an internal supersonic compression air intake under conditions of contraction for which the start-up in permanent regime is theoretically impossible (Fig.7). In the same diagram, the ratio of entrance to exit sections is 2.25 whereas, theoretically, this ratio in permanent regime cannot exceed 1.6. This test offers interesting prospects for the study and application of such air intakes in hypersonic flow.

Figure 8 shows a test setup for studying the effects of blasts produced /5 by an explosion or a gust on a model in supersonic flight. The blast effect is obtained by a very small shock tube whose orifice is placed on the lateral wall of the nozzle. This shock tube can also be mounted along the axis to simulate a longitudinal gust. Observation is done over an electronic image converter, giving exposure times of 1 nanosec at adjustable time intervals.

The test chamber of the R2 and R3 wind tunnels was designed so as to accommodate a magnetic suspension investigated at the ONERA (Ref.3) which prevents any interaction between support and flow around the model (Fig.9). This device has been successfully used in analyses of the structure of hypersonic wakes: It is known that the stings of conventional suspensions will produce parasite wakes which completely distort the main phenomenon, specifically the conditions of transition to the turbulent regime.

The research on these problems performed in collaboration with the ISL will permit highly instructive intersections between the results of the launch tube and those obtained in the wind tunnel by means of this magnetic suspension.

2. Wind Tunnel R4 Ch ($M \leq 15$)

The experimental difficulties encountered at Mach numbers between $M = 10$ and $M = 20$ in relatively high-temperature wind tunnels (shock tunnel, reflected-shock tunnel, hot shot) induced us to develop a hypersonic test facility in the above Mach number domain, having a temperature just sufficient to prevent liquefaction but characterized by an extremely clean flow (highly stable pressure, absence of dust, quasi-constant temperature for a run of about 100 msec).

The operating principle used is that of heating the air by slow compression (Fig.10). A piston, activated by very gradually supplied compressed air, compresses and reheats the air previously stored in a tube of 13 m length (inside diameter = 120 mm) heated to 600°K. The piston travel is about 1 sec and, at the end, the temperature reaches approximately 1650°K and the pressure 200 atm. A suitably calibrated plug, inserted at the nozzle throat, is then ejected and the run is started: The piston, at constant pressure, repulses the air of the gust whose temperature fluctuates little during the test which takes 150 msec in a Mach 14 nozzle with an exit diameter of $\sim$ 30 cm.

This wind tunnel, which is in operation now (Ref.4), has already permitted highly reliable tests and has an excellent Mach 14 nozzle (Fig.11). We consider this tunnel as a true standard hypersonic wind tunnel.

3. Wind Tunnels ARC 1 and 2 (Fig.12)

At the time that, in 1958, the problem of creating test facilities for elevated temperatures at M = 16 was posed at the ONERA, our selection fell on the principle of the hot shot which then (Ref.5) seemed the only test facility for obtaining temperatures of the order of 5000°K during gusts of several tens of milliseconds (the shock tunnel or the reflected-shock tunnel were unable to produce gusts longer than a few milliseconds and thus remained within the domain of short runs, which we had reserved for the ISL according to agreement; see Introduction).

The problem to be solved here was to rapidly heat a gas mass of the order of 500 gm so as to raise its pressure to 1000 or 2000 atm and its temperature to at least 5000°K. This could be done only by an electric arc operating in an enclosure. The energy to be produced was of the order of 10 MJ (megajoules) which, assuming a heating time of the order of 1/100 sec, meant an instantaneous power of 10^6 kw.

After studying the various power sources used in the USA (capacitors, unipolar short-circuited dynamo), it seemed to us that, within the existing deadlines and at the funding available, none of these solutions was practicable. On suggestion by R.Legendre, Technical Director of the ONERA, we then decided - with the approval and cooperation of the EDF - to operate by extremely brief short-circuits of the French State-owned grid system. Incidentally, this operation was possible only within the scope of the research done by the EDF at Fontenay where powerful circuit breakers are available in addition to a power network laid out so that such short-circuits will not interfere with outside users. Thus, from the very beginning we had a useful power of the order of 10 - 100 MJ available, i.e., a power greater than that of the largest hot shot of the AEDC at Tullahoma.

Figure 12 gives a block diagram of this installation, constructed in record time since the decision to build had been taken at the end of December 1958 and the first run was to be made in January 1960. Naturally, not everything was perfect as yet and it is not surprising that it took several years of patient effort and extreme tenacity to overcome the great difficulties in fully developing the facility.

Two extremely simple concepts have permitted decisive progress in this direction:

Primarily, this consisted in replacing the diaphragms, used everywhere for arresting the flow during the heating phase, by a simple conical plug of plastic material, calibrated so that it is pushed out at the maximum prescribed pressure and beveled at its posterior end so that it is ejected obliquely along the profile of the nozzle. This procedure greatly simplifies the internal design of the arc chamber and, on the model, prevents any projections due to rupture of the diaphragm.

The second improvement was obtained by using a double high-pressure chamber. In the original system based on American designs, it was impossible to prevent pressure and temperature fluctuations during blowdown; under such conditions, the six-component measurements and the pressure measurements were moderately useful while the flux measurements were extremely poor. In addition, it was difficult to obtain reproducible test conditions at will.

We then thought that this heterogeneity might be due to the fact that, in the arc chamber, only a portion of the gases is exposed directly to the arc and thus is heated to temperatures of the order of 20,000°K. These gases do not mix sufficiently rapidly with the colder gases which had been heated primarily by adiabatic compression, so that, due to the eddies generated in the arc chamber during the blow, either a burst of cold gases or a burst of extremely hot gases collected in front of the throat and was ejected into the nozzle. These temperature fluctuations produced excessive variations in the thickness of the boundary layer of the nozzle and, consequently, fluctuations in the Mach number and pressure at the exit of the nozzle. To obtain a more efficacious homogenization, we proposed to insert, between the arc chamber and the collector of the nozzle, an initially exhausted intermediate chamber isolated instantaneously from the arc chamber by a plug playing the role of the first diaphragm. This plug is calibrated so as to pop at a predetermined level of pressure in the arc chamber. At this instant, the intermediate chamber is filled and the gases, injected at high velocity, are intimately mixed in this chamber before the plug of the nozzle is able to pop, producing the blowdown. /7

In addition to the thorough mixing, this has two important advantages: First, by properly selecting the operating pressure of the intermediate plug and that of the nozzle plug, one can arbitrarily make tests at initially increasing or decreasing pressure. In fact, this makes it possible to obtain quasi-isobaric gusts over a time of more than 50 msec whereas, in the conventional system, the pressure decreases constantly during the test. In addition, the constant-volume filling of the intermediate chamber from the arc chamber, in accordance with the Prandtl theorem, theoretically permits obtaining an initial temperature $\frac{C_p}{C_v}$ much higher than that of the arc chamber.

The resultant progress is quite significant (Fig.13). As a typical example, Fig.14 gives the gross results of a recent sounding of the nozzle by Pitot tubes, carried out downstream of the model: Specifically, there were distinct turbulent zones of the boundary layer, along with a very calm nonviscous flow zone and a low-pressure stagnation zone which corresponded to the viscous and apparently laminar wake of the model.

In the ARC 1 wind tunnel, the same tests are being carried out as in the other gust tunnels, using the same type method, since the useful runtime of the blow is about 100 msec which raises no serious problems.

Recently, we installed (Ref.6) in the ARC 1 tunnel a device for determining the pressure distribution over about 20 parallels, during one and the same blowdown, by rotating a model of revolution at a certain angle of attack a half-turn about its axis; this obviously is of considerable experimental interest. Similarly, the three-component measurements were obtained in a single run on a model whose angle of attack was varied by 20° (Fig.15).

Figure 16 gives a typical example of thermal flux measurements in the standard HB2 wind tunnel of the AGARD, compared to tests made by the AEDC (Tullahoma). The scattering of the test data observed in the ARC 1 tunnel at low flux values is due primarily to the poor sensitivity of the microprobes available today.

Figure 17 shows schlieren pictures of a plane plate, mounted in the ARC 1 tunnel for studying the viscous interaction at M = 16; it is easy to discern the zone with a high density gradient, marking the transition between the laminar boundary layer and the external entropy layer (Ref.7). /8

It is known that the use of elevated temperatures in hypersonic wind tunnels encounters basic difficulties due to the frozen flow of chemical reactions in the zone of the nozzle throat. Even when limiting the tests to moderate temperatures (3000 - 4000°K) and using nitrogen, the tests in the ARC wind tunnels still show these difficulties. Figure 18, due to a study by F.Bouniol, shows that the freezing of the vibration of the nitrogen molecules takes place shortly aft of the throat and affects a relatively large portion of the total energy.

In our present research on ionized wake problems, we started using air instead of nitrogen to accentuate the ionization phenomena of the plasma around a re-entry model. Apparently, the quality of the flow is not greatly affected by this, but it is obvious that processing of the data raises difficult problems for whose solution we anticipate a close collaboration with the Research Institute of Saint-Louis.

In view of a detailed study of problems of electromagnetic wave propagation through the plasma of re-entry, we are now building, along the same principles, an ARC 2 wind tunnel whose test section which, at first will be 0.75 m and later 1.20 m, is to be constructed entirely of plastics over a length of several meters.

Conclusions

This brief review hopefully has given a general idea on the present facilities of the ONERA for hypersonic research. Although they form a coherent system, these test facilities are not sufficient for covering all needs and requirements in this field; fortunately, they are complemented by the ballistic testing facilities developed at the Research Institute of Saint-Louis and at the Ballistic and Aerodynamic Laboratory of Vernon, as well as by the hypersonic shock or reflected-shock tunnels available at the Research Institute of Saint-Louis, at the Fluid Mechanics Institute of Marseilles, and at Sud-Aviation in addition to the low-density wind tunnels installed at the Aerothermics Laboratory of the National Scientific Research Center at Bellevue.

The fruitful collaboration, developed between the various organizations and gradually extending to the German counterparts, offers great promise for hypersonic research on the European plane.

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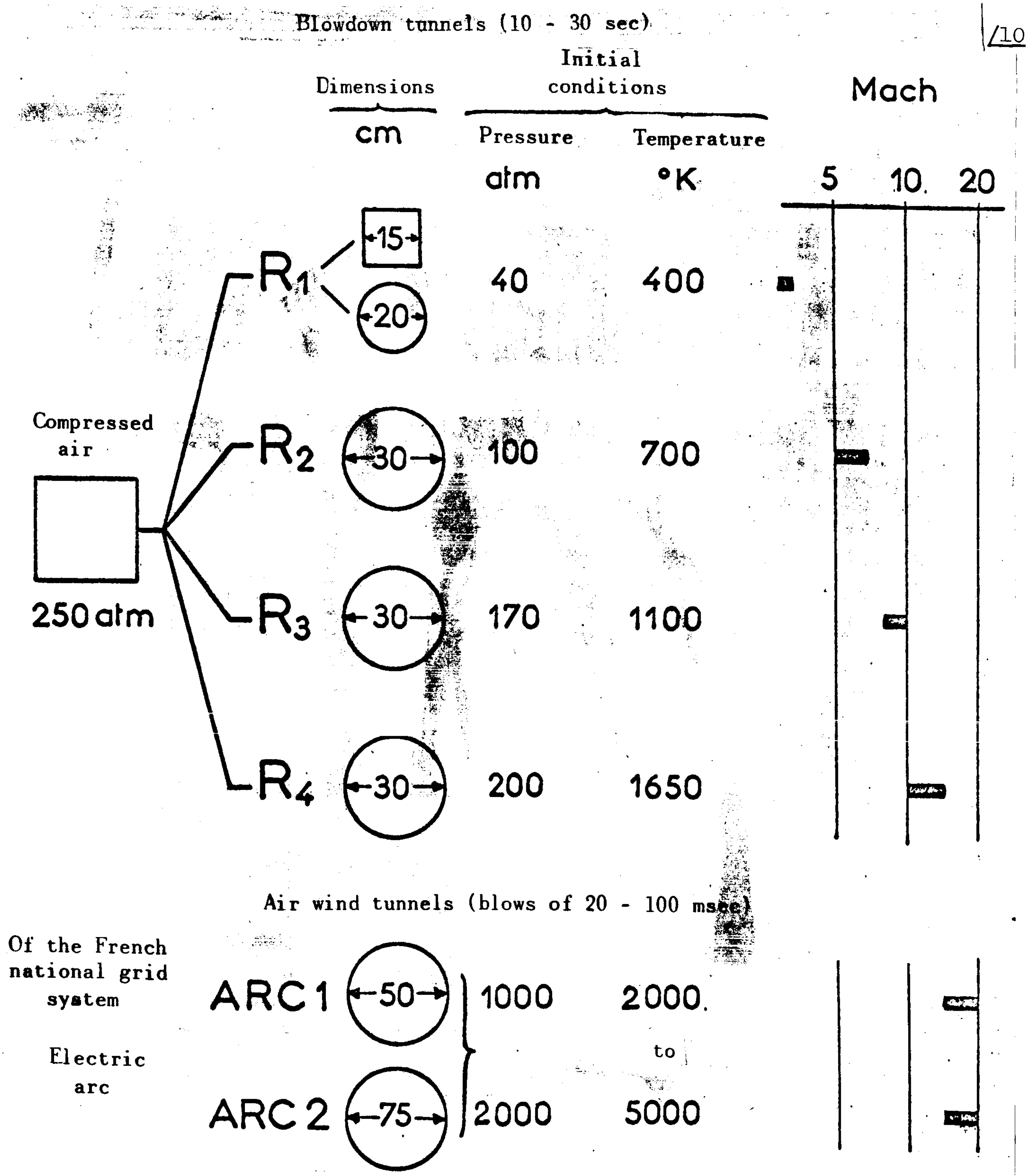

Fig.1 Hypersonic Wind Tunnels of the ONERA.

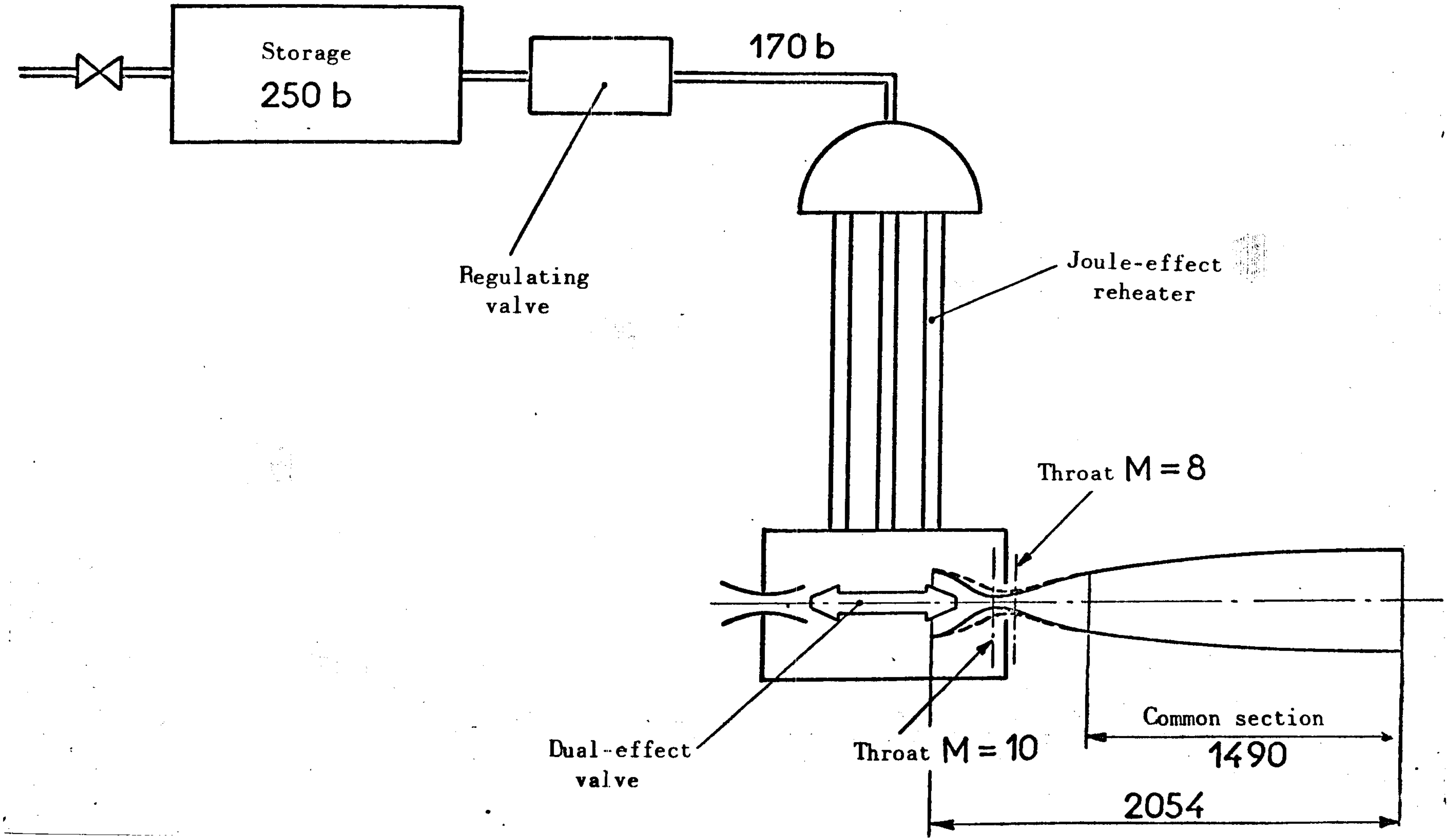

Fig.2 Flow Sheet of the R_3CH Wind Tunnel.

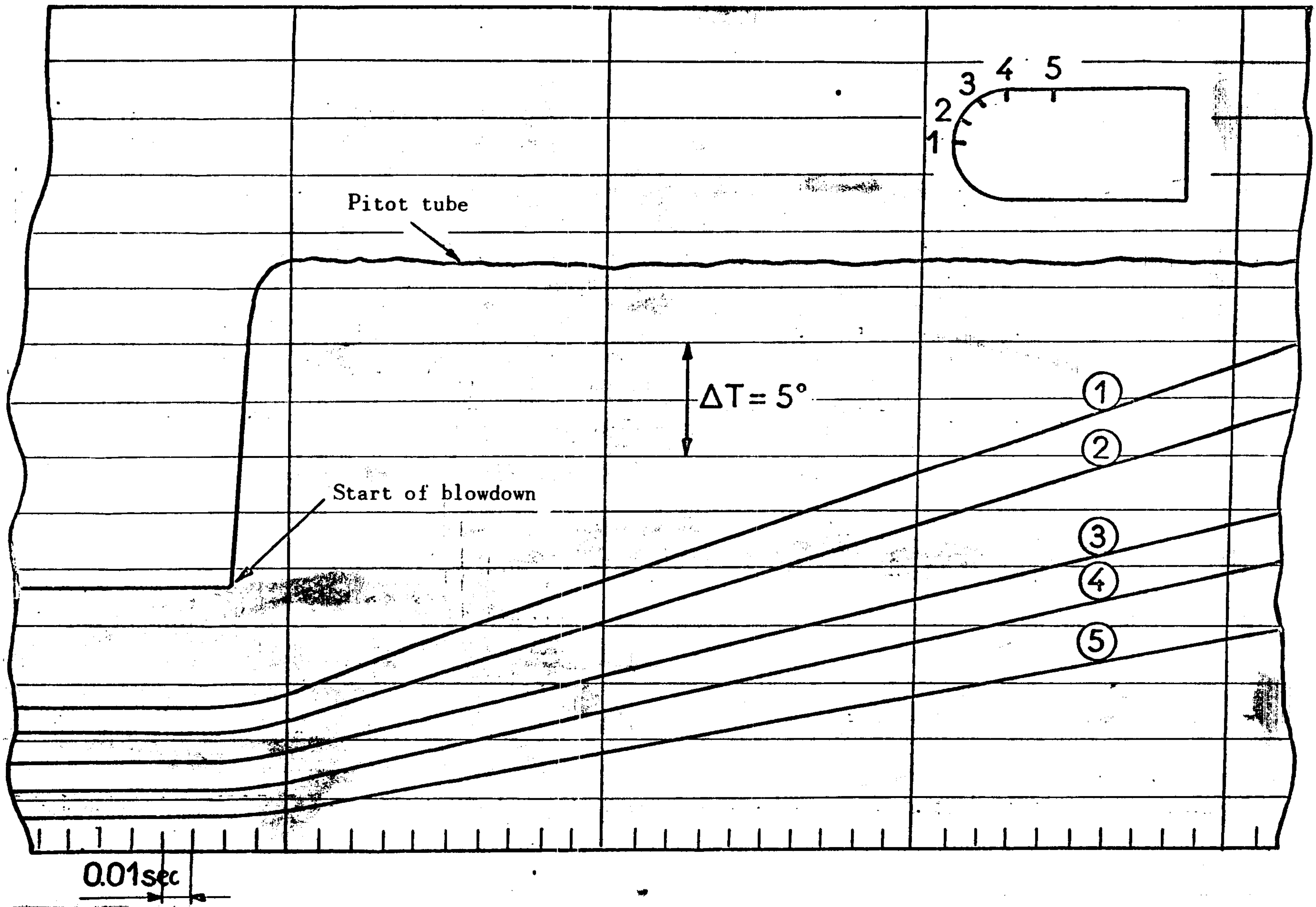

Fig.3 R_3CH Tunnel; Response Curve of the Wall Thermocouples.

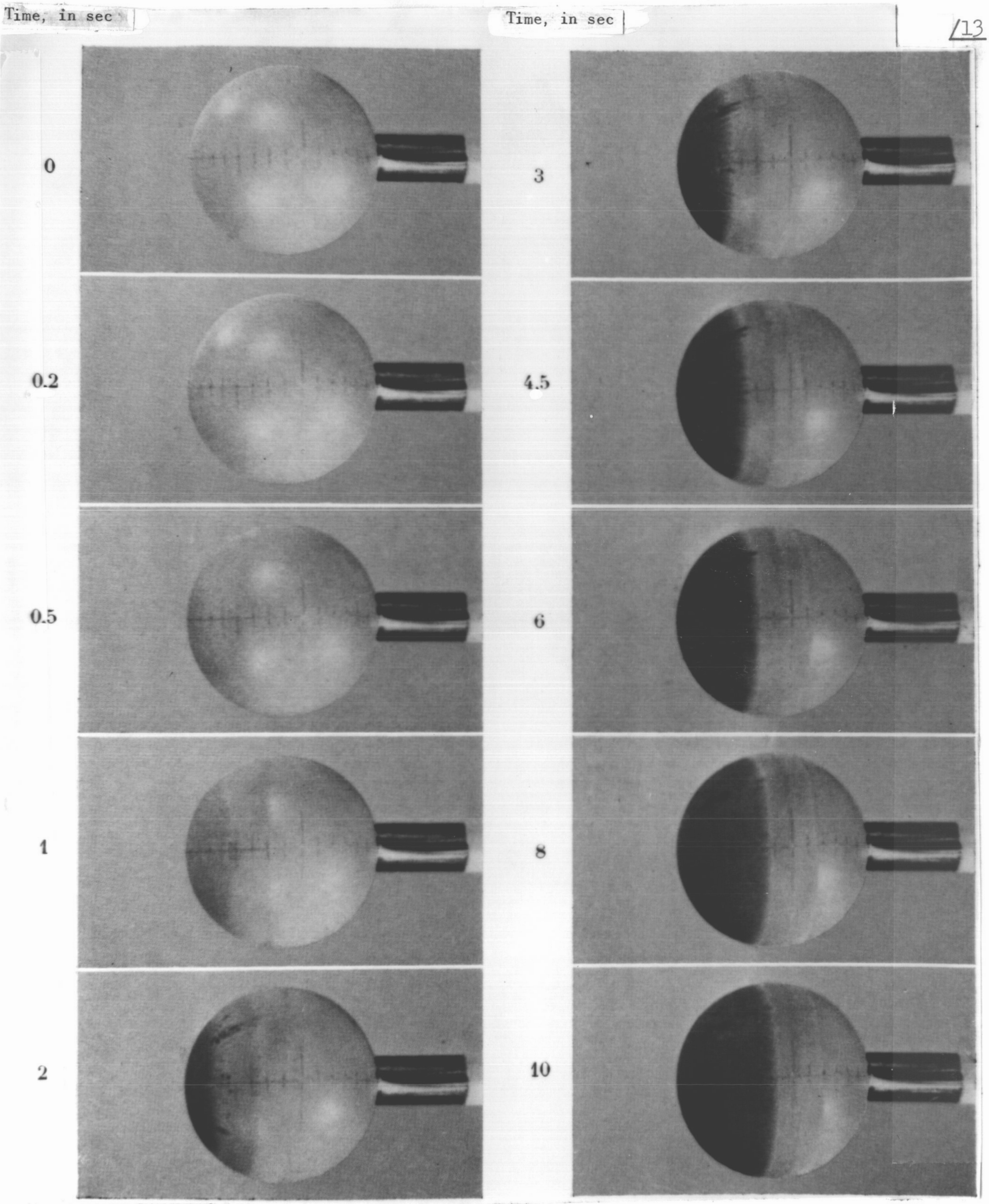

Plate 2 Heating of a "Silastene" Sphere of 60 mm Diameter.

Ballistic nose cone

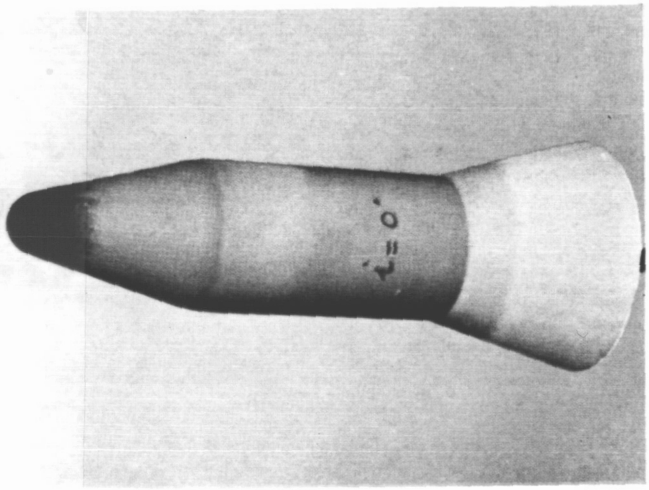

Fig. 4. — Incidence 0°

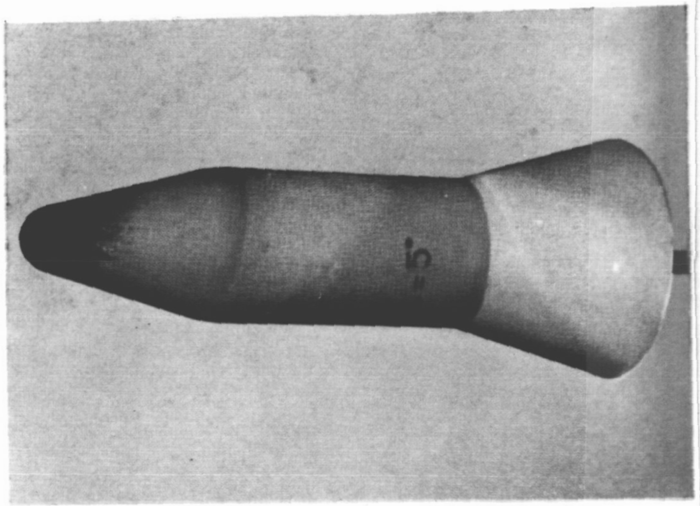

Fig. 5. — Incidence 5°

Hypersonic glider
Incidence $i = 15°$; Sideslip $j = -15°$

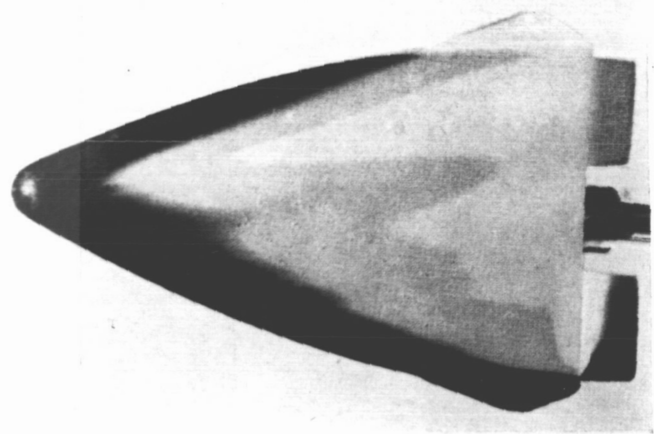

Fig. 6. — Bottom View (Pressure Side)

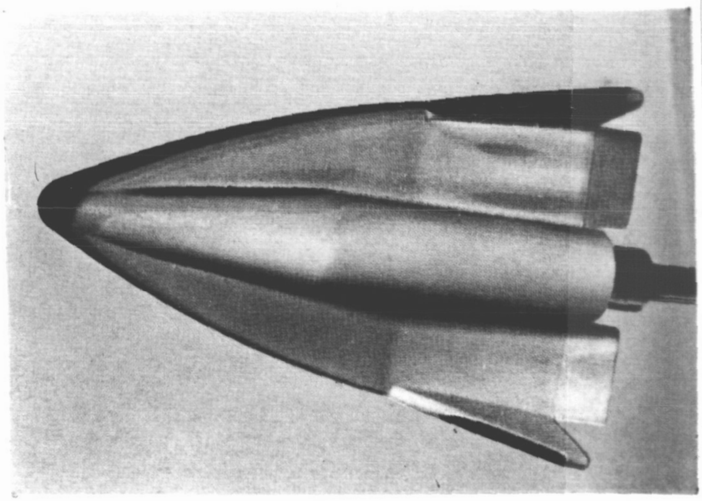

Fig. 7. — Top View (Suction Side)

Plate 4 - 7 Visual Display of Kinetic Heating by Thermocolor Coating; Test in the R3 Chalais Wind Tunnel at M = 10; $T_1 = 1000°K$; Test Run: 10 sec.

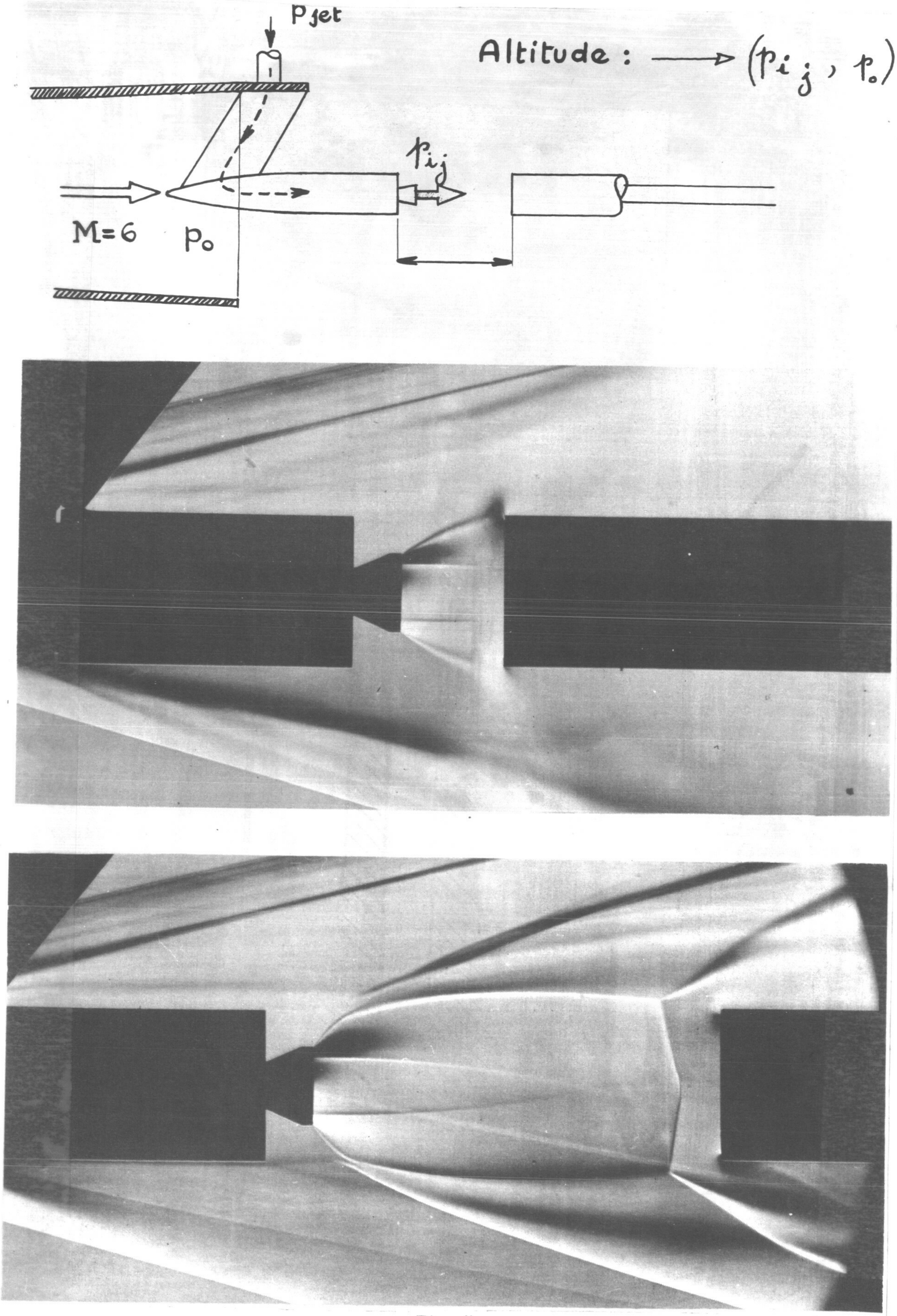

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Fig.5

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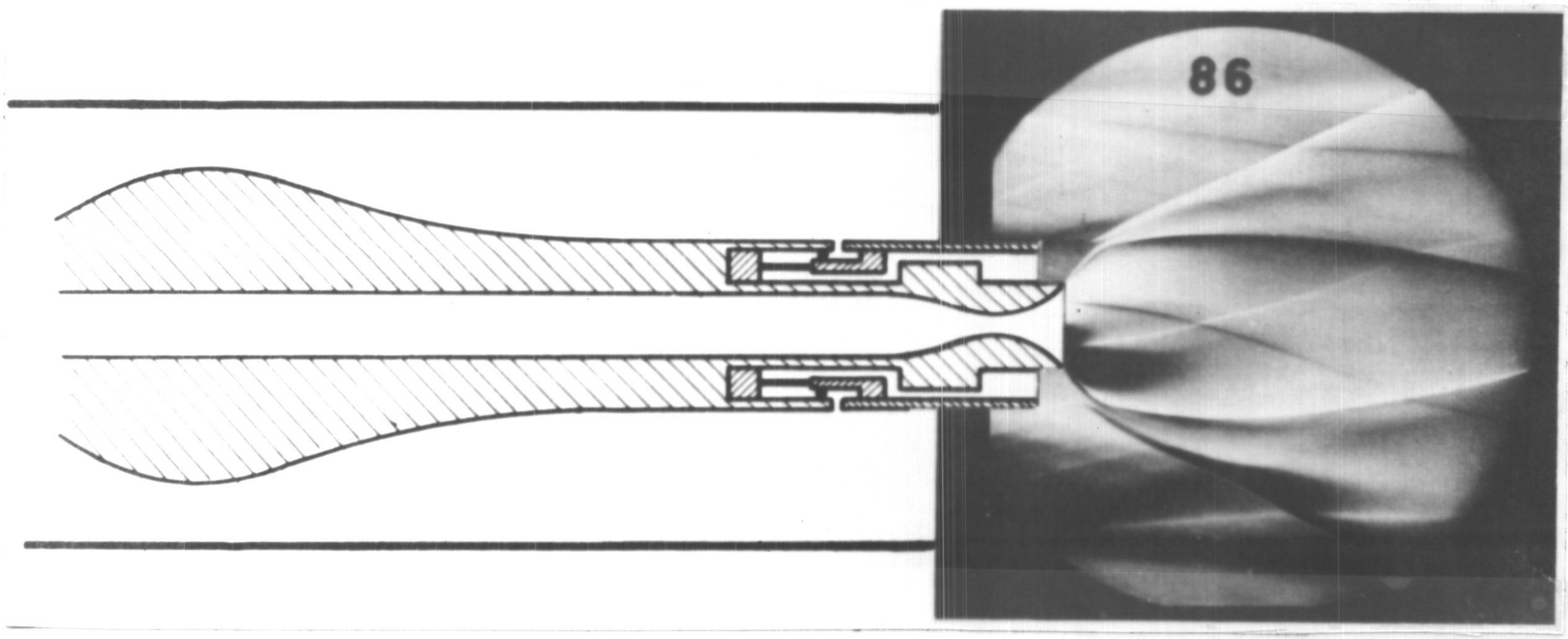
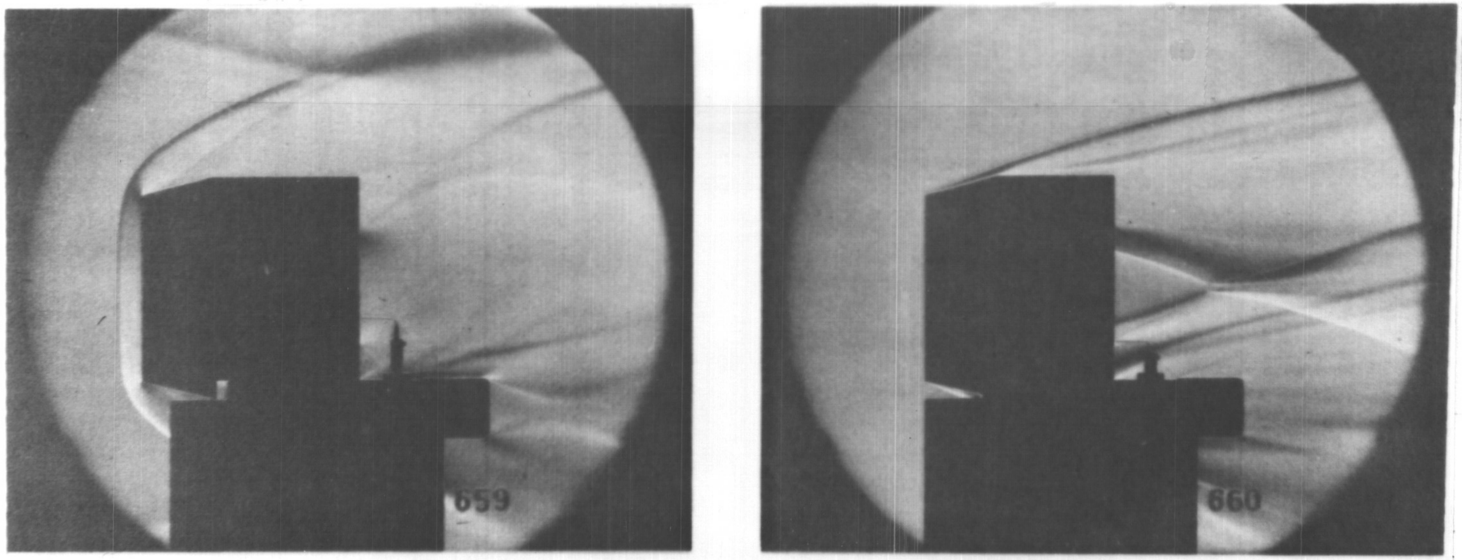


Fig.6 R_1CH Tunnel; Thrust of an Aft Section of the Rocket in the Presence of a Jet.



Start-up in transitory
regime

Fig.7 Internal Supersonic Compression Air Intake.

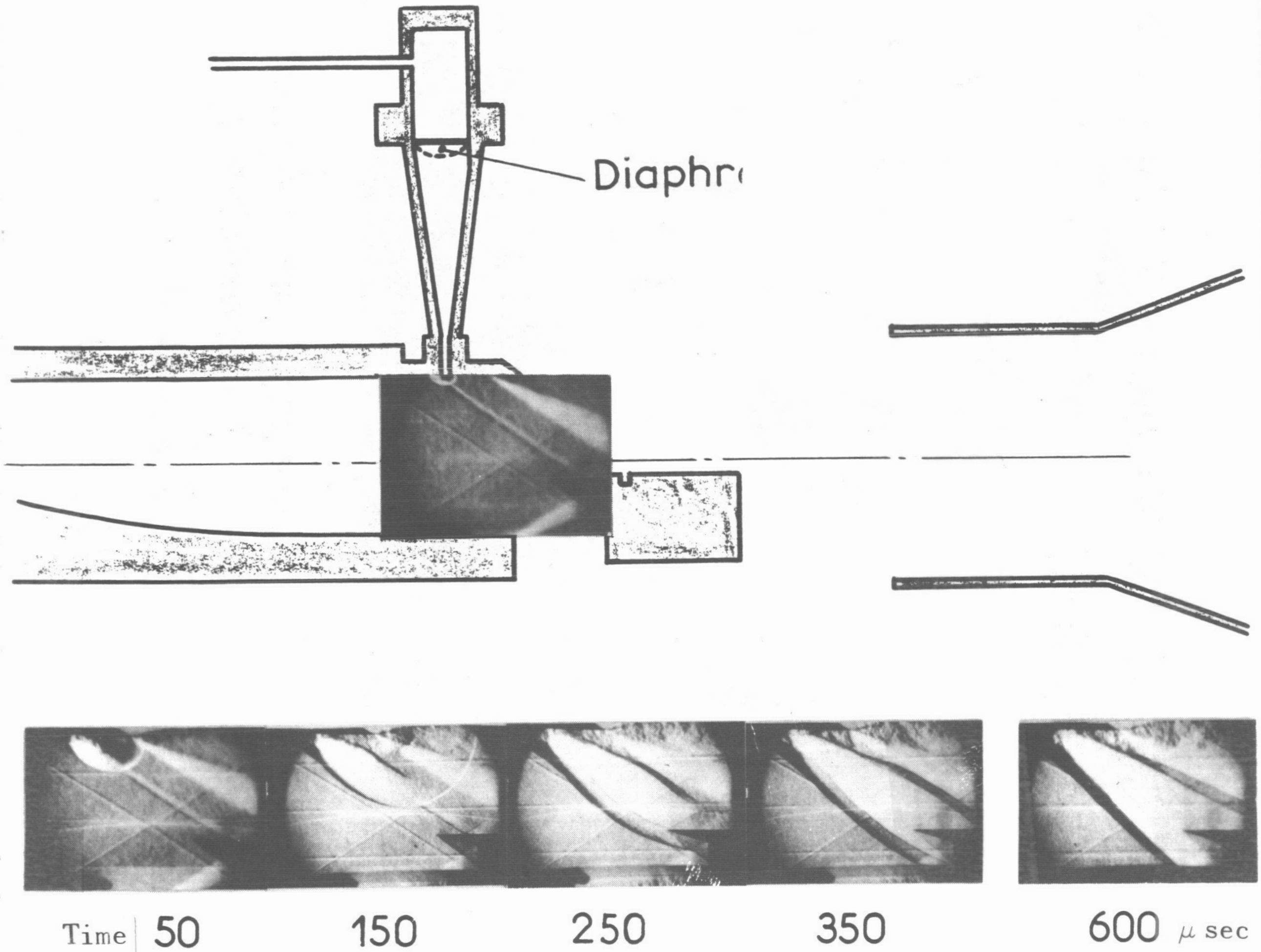


Fig.8 R_1CH Tunnel; Simulation of a Blast Effect at M = 1.9.

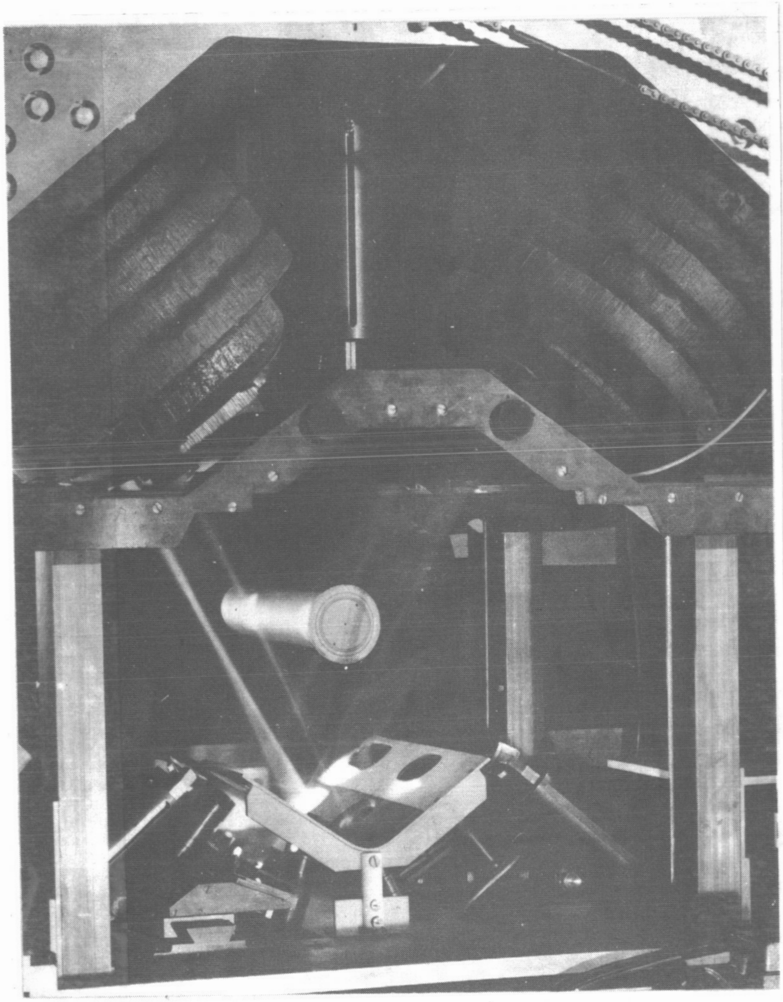


Fig.9 Magnetic Suspension.

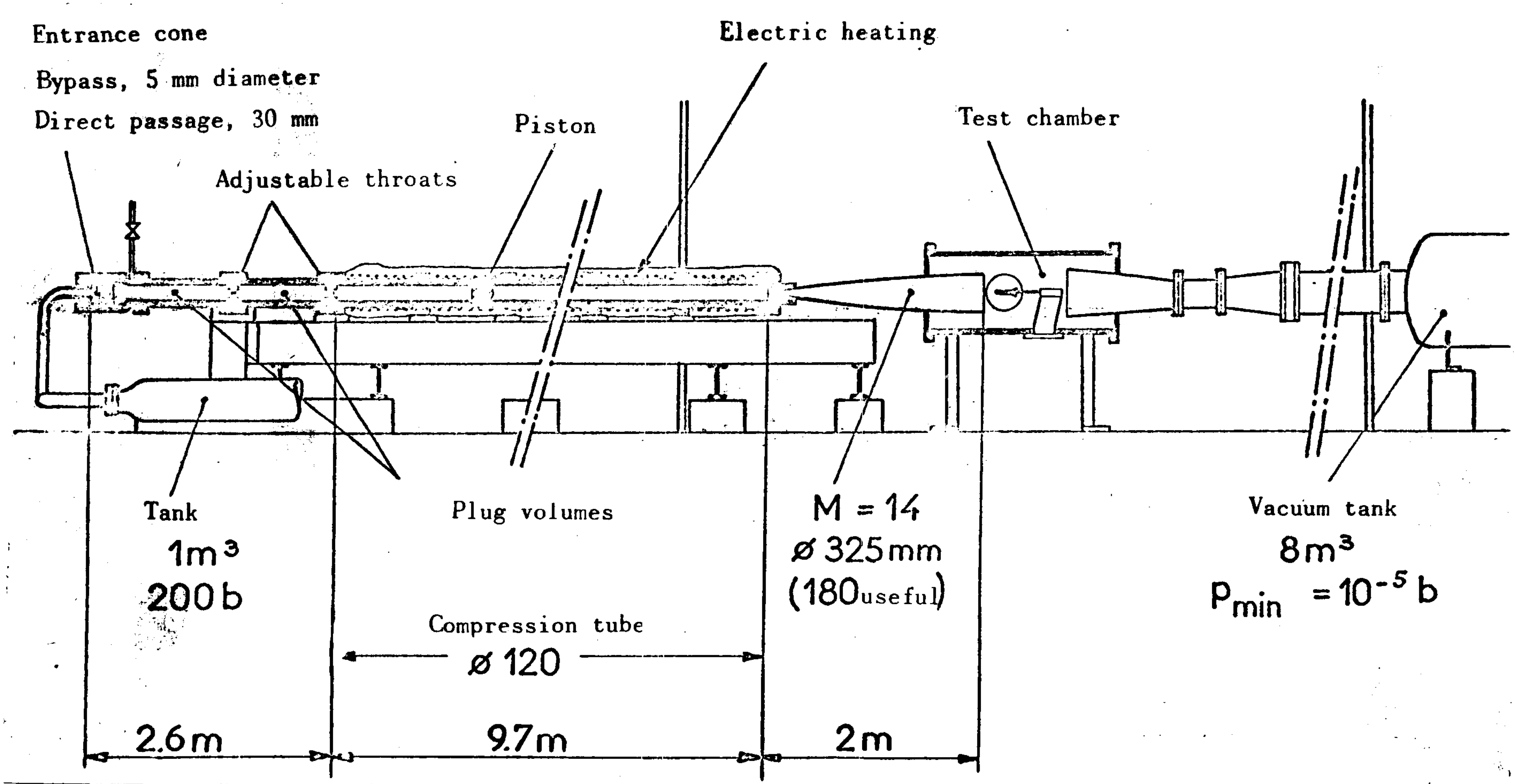


Fig.10 R_4CH Tunnel; Overall View.

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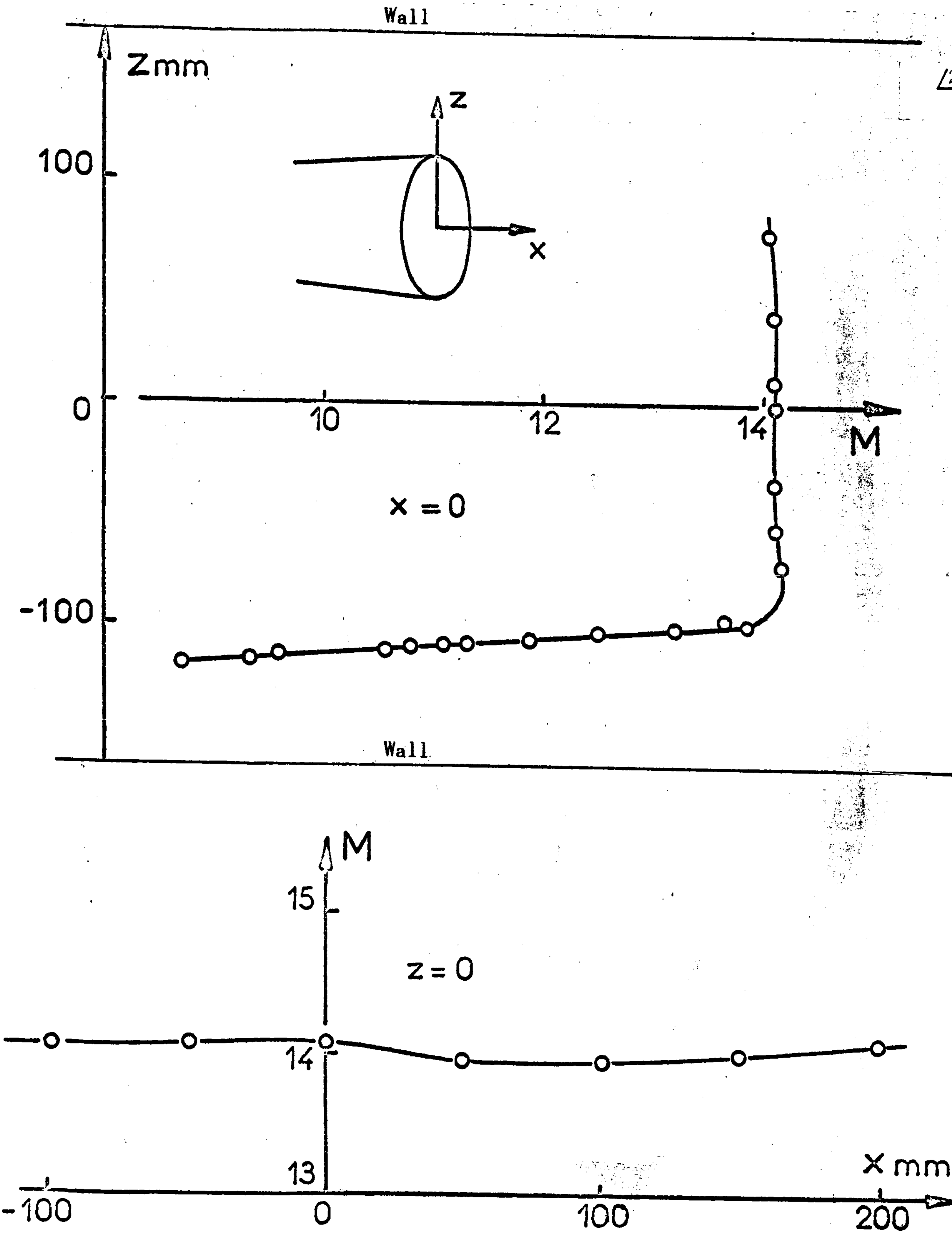

Fig.11 R_4CH Tunnel; Sounding of the Mach 14 Nozzle.

/22

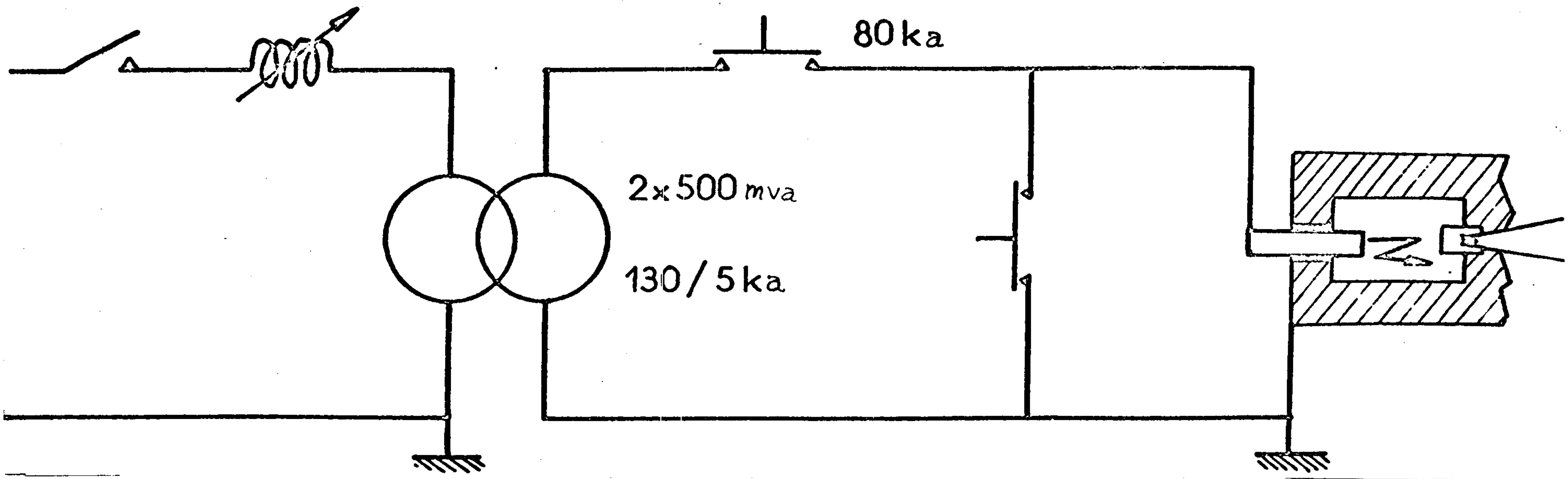

Fig.12 Arc Tunnel; Electric Power Supply.

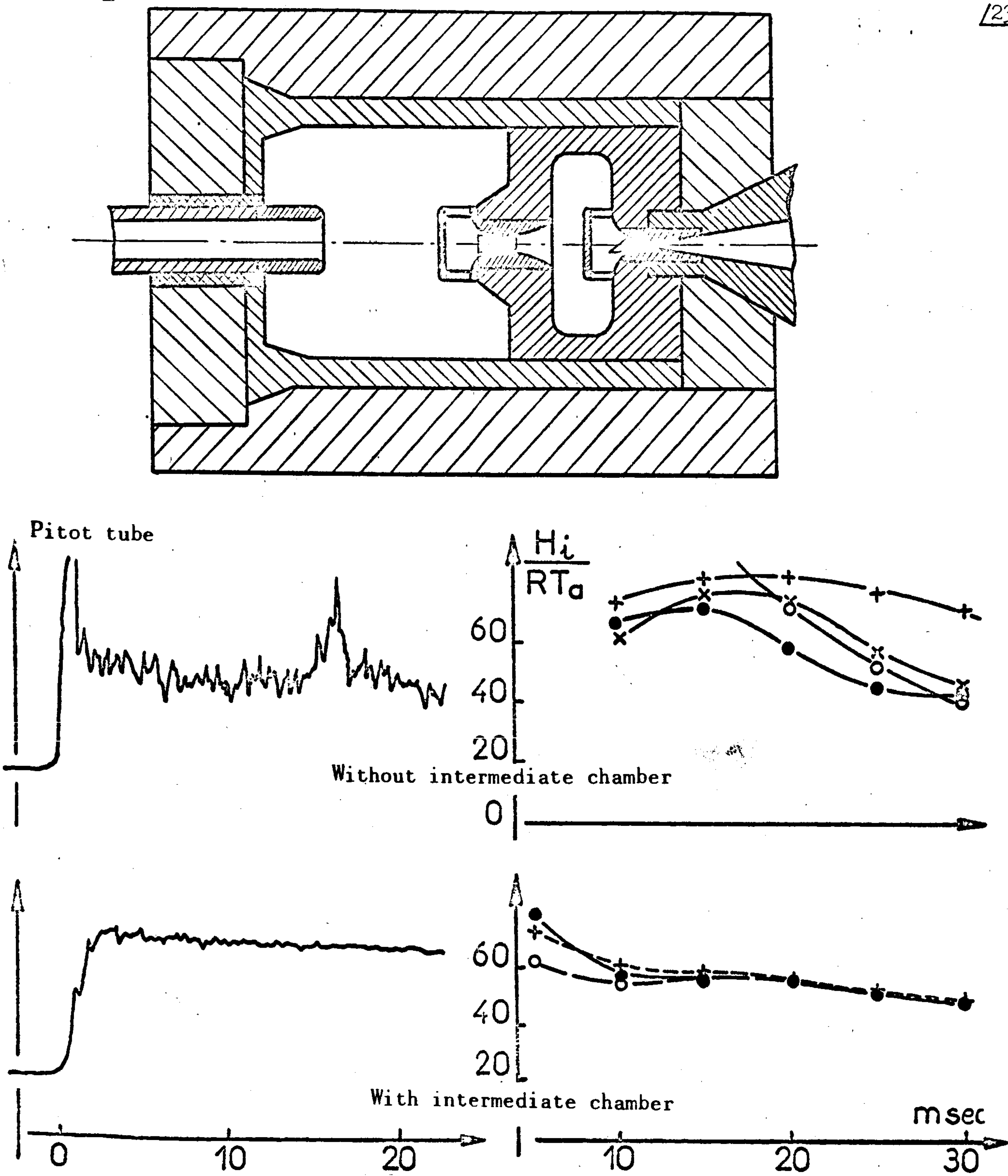

Fig.13 ARC2 Tunnel; View of the Intermediate Chamber.

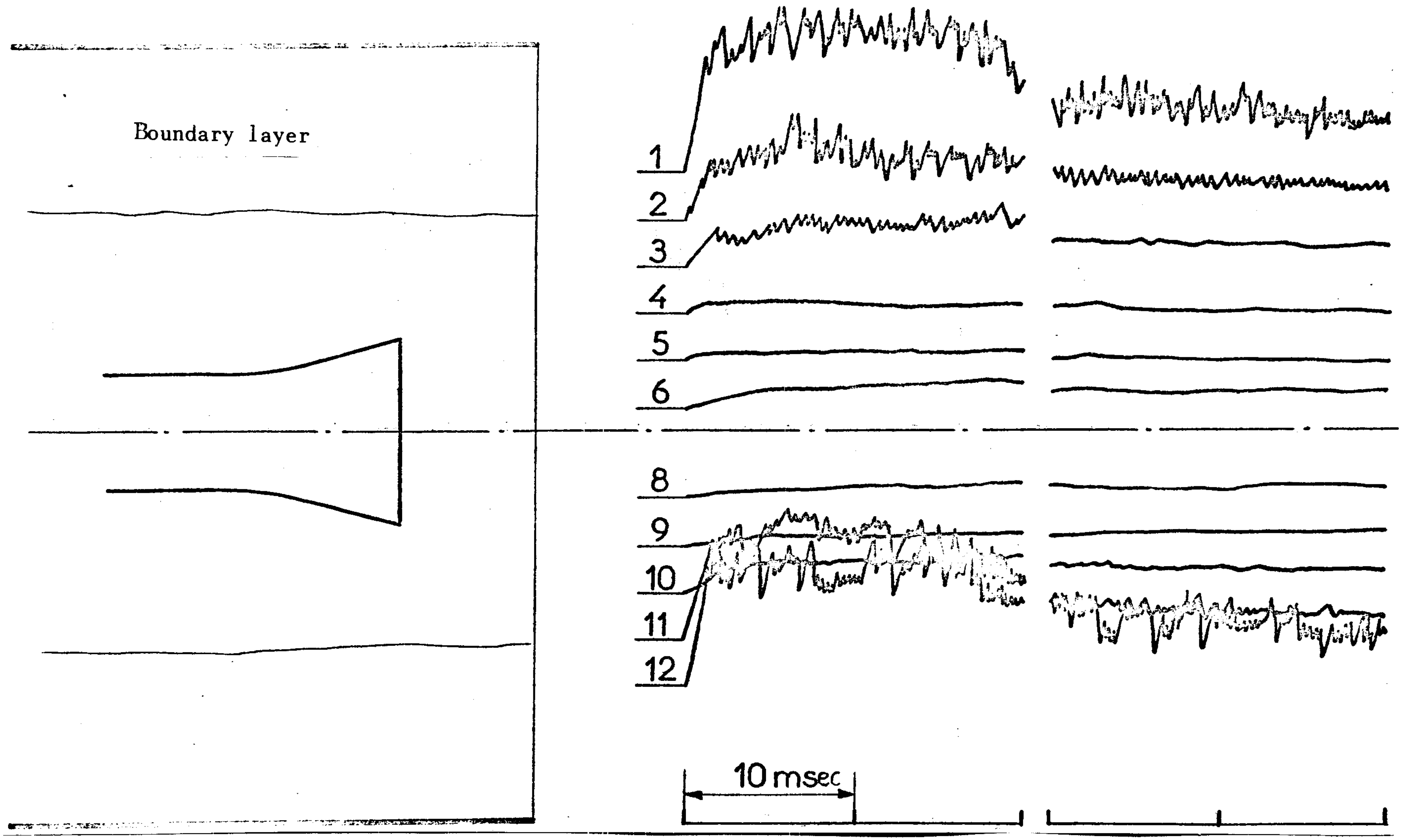

Fig.14 ARC2 Tunnel; Pitot-Tube Sounding of the Nozzle Downstream of a Model.

/24

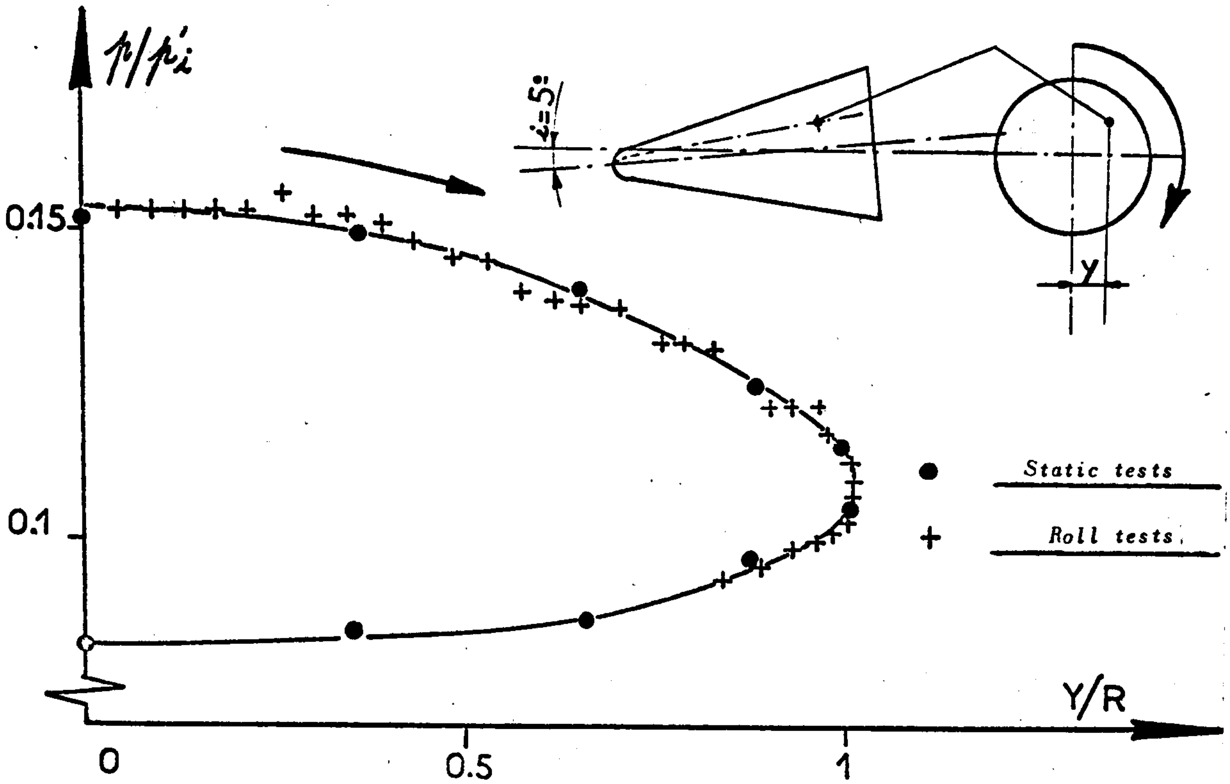

Fig.15 Pressure Distribution Measurement
during Blowdown.

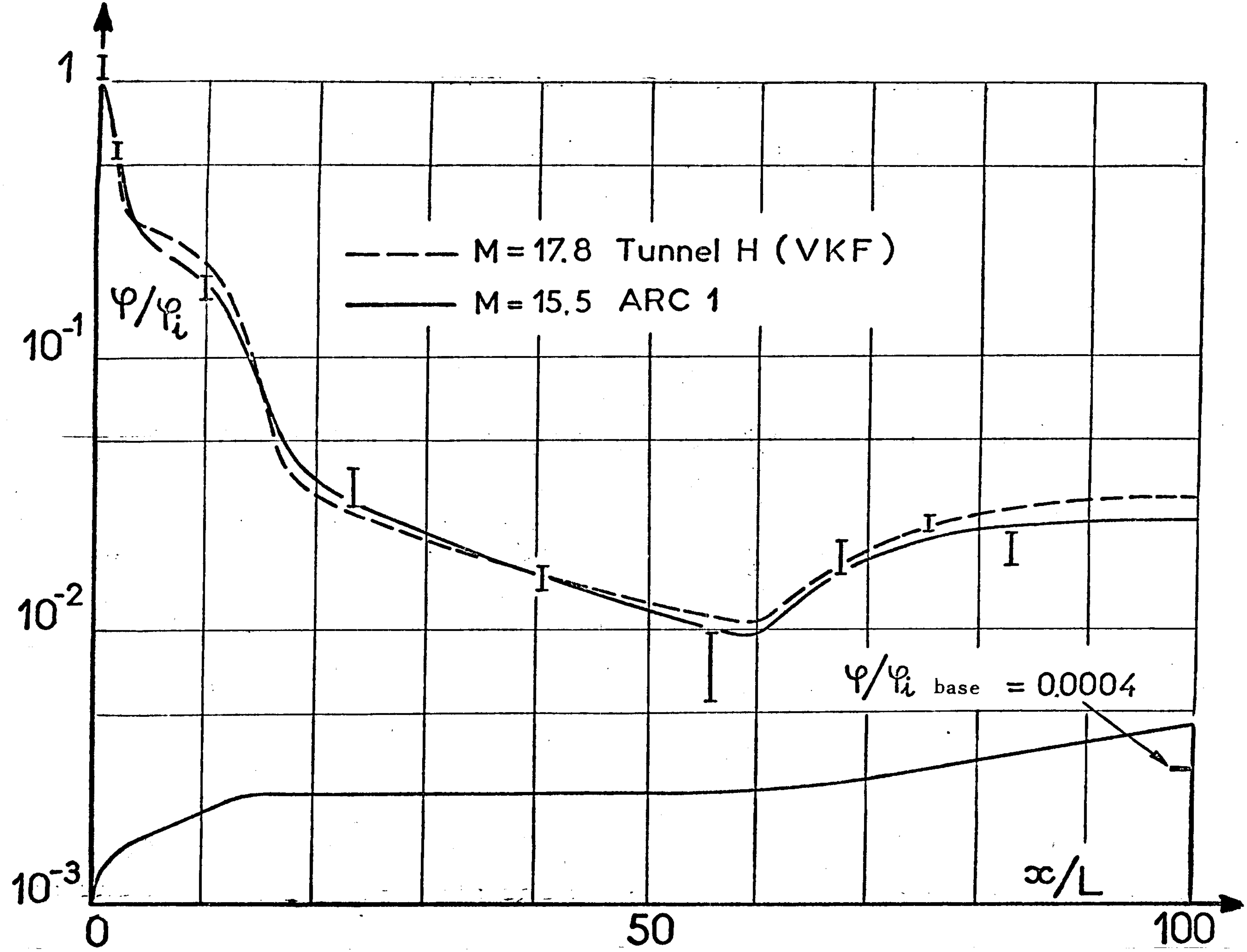

Fig.16 ARC1 Tunnel; Heat Flux in the HB2 Standard Tunnel.

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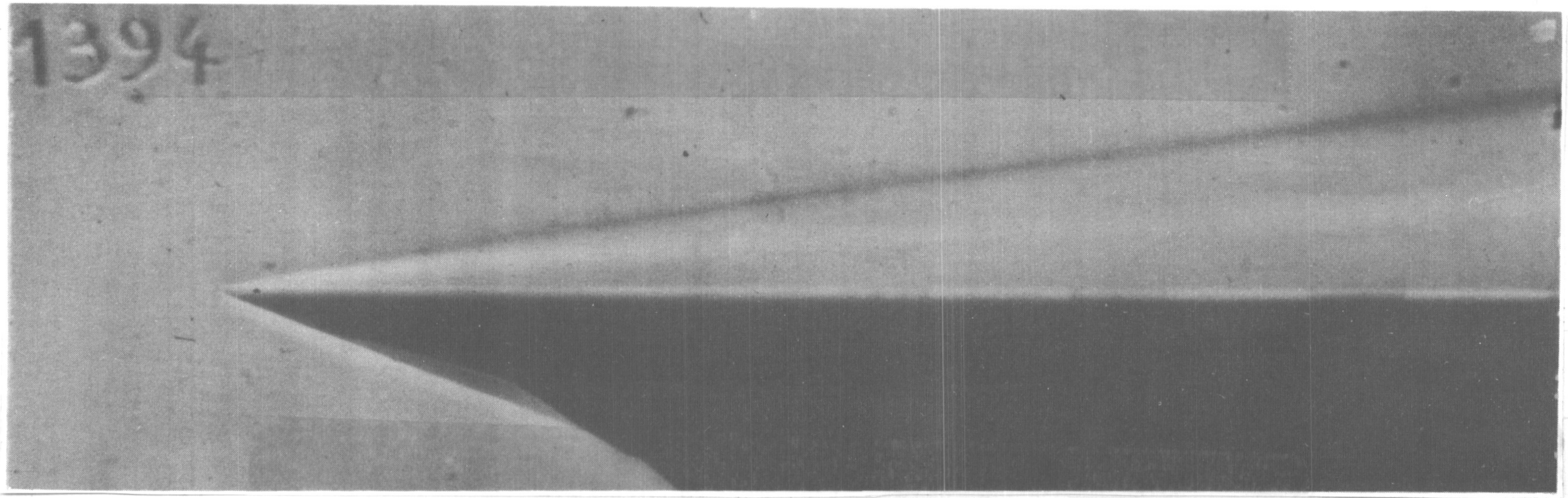

$M = 16 \qquad \frac{\rho}{\rho_a} = 10^{-3}$

Fig.17 Schlieren Picture on a Plane Plate.

/28

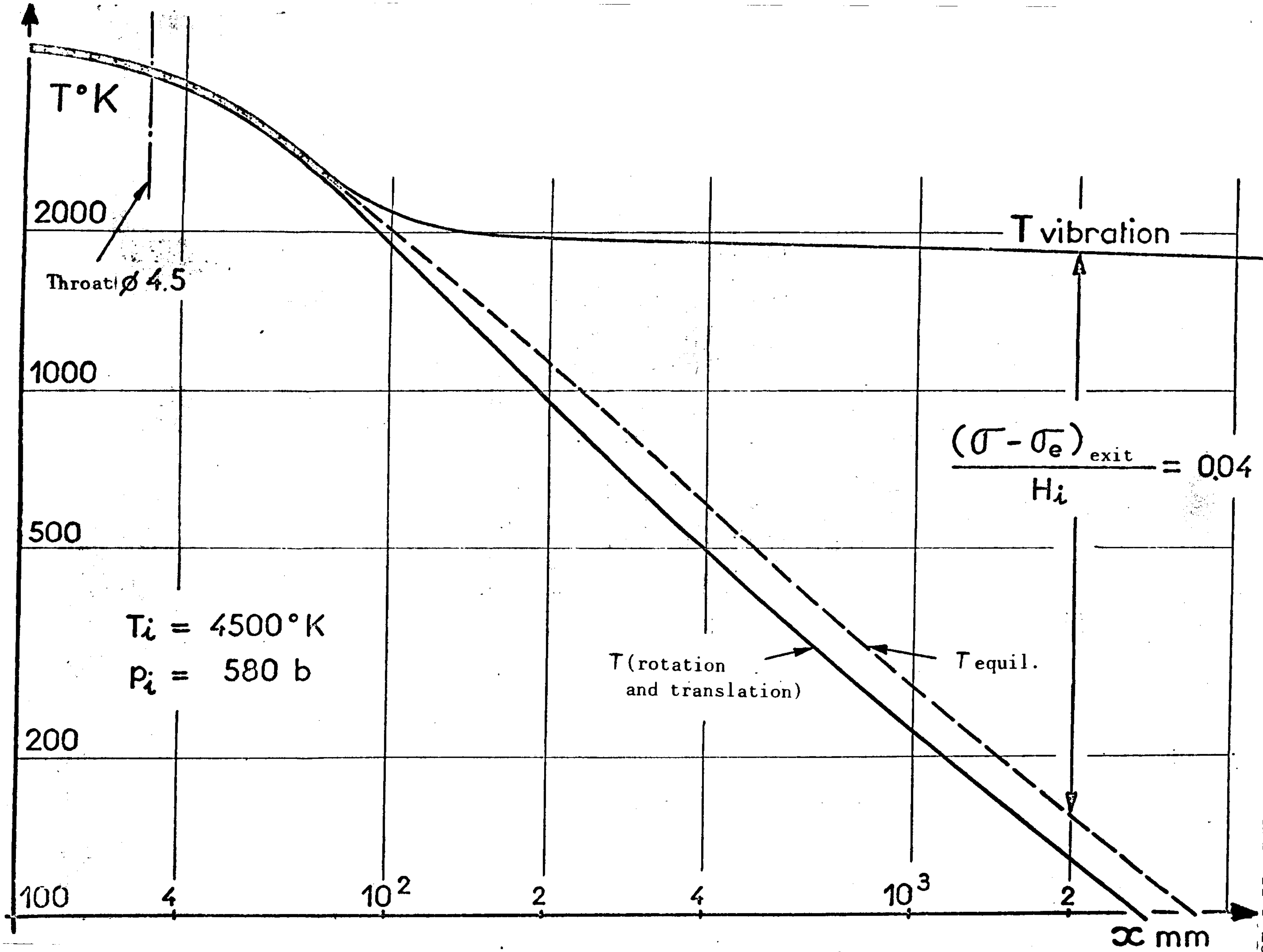

Fig.18 ARC1 Tunnel; Theoretical Evolution of Temperatures in Nonequilibrium.